

Identification of trailing edge solar wind stream interfaces: A comparison of Ulysses plasma and composition measurements

M. E. Burton,¹ M. Neugebauer,¹ N. U. Crooker,² R. von Steiger,³ and E. J. Smith¹

Abstract. Measurements of the specific entropy argument of the solar wind protons, $T/n\gamma^{-1}$, reveal that nearly every occurrence of a high-speed stream seen at Ulysses in 1992-1993 is characterized by an abrupt interface at its trailing edge. These observations, made by the solar wind plasma instrument (SWOOPS), at a heliocentric range of 4.5 to 5 AU show that there is a discontinuous drop in specific entropy at the interface from a high value in the high-speed wind to a lower value in the slow interstream wind. This interface is coincident with, but much more abrupt than, compositional changes measured by the Solar Wind Ion Composition Spectrometer (SWICS) [Geiss *et al.*, 1995]. These results suggest that a relatively thin interface can be identified which separates two plasmas of distinctly different origins as determined by the compositional measurements. A superposed epoch analysis performed on seventeen events reveal the interface is characterized by (1) an abrupt drop in entropy by a factor of $\sim 1/3$ due to an enhancement in density along with gradually declining temperature, (2) a distinct drop in the alpha/proton ratio from a value of $\sim 5\%$, typical of the fast wind, to $\sim 4\%$ characteristic of the slow solar wind, and (3) relative changes in Mg^{10+}/O^{6+} at the interface which are as large as the variations in the total Mg/O ratio and the freezing-in temperature derived from O^{7+}/O^{6+} . The specific entropy argument, a combination of commonly measured solar wind parameters, gives a strong signature of the trailing edge interface which is preserved as far out in the heliosphere as 5 AU and may provide useful information regarding the coronal origin of solar wind streams.

1. Introduction

In early 1992, at 13° S latitude, in transit to the southern solar pole, Ulysses began to sample a recurrent high-speed solar wind stream which emanated from a coronal hole at the south pole of the Sun. This recurrent stream was seen regularly each solar rotation at a heliocentric distance of roughly 4.5 to 5 AU until the spacecraft was continuously immersed in high-speed solar wind by 36° S latitude. The solar wind plasma instrument (SWOOPS) provides 4 to 8 min resolution of the proton density and kinetic temperature. A detailed description of the instrument is provided by Bame *et al.* [1992] and a summary of the observations of these streams in the work of Bame *et al.* [1993].

During this time the Solar Wind Ion Composition Spectrometer (SWICS) onboard Ulysses made continuous composition and charge state measurements of all major solar wind ions [Gloeckler *et al.*, 1992]. The charge states of the heavy ions measured by that instrument can be used to infer the coronal temperature, since they are frozen-in near the altitude in the corona where the expansion timescale overcomes the ionization/recombination time scales. Elemental abundances of heavy ions are found to be different in the solar wind as

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compared to the photosphere (referred to as fractionation) and this fractionation is best organized by the first ionization potential (FIP) of the element. Since the first ionization occurs in the upper chromosphere, solar wind abundances are indicative of conditions there. The ratio of a pair of high and low-FIP elements such as Mg/O has been used as a proxy for the strength of the FIP effect. These ideas are discussed in detail by *Von Steiger* [1996]. Patterns in the variations of the Mg/O and the coronal freezing-in temperature obtained from the O^{7+}/O^{6+} charge state have been found to be virtually identical to each other and anticorrelated with the solar wind velocity [*Geiss et al.*, 1995]. Further, an abrupt transition between high and low values of these parameters was observed at both the leading and trailing edges of the stream. A superposed epoch analysis of these data is reproduced in Figure 1. These observations are significant since they suggest that the chromosphere and corona have a common, sharp boundary separating the low- from the high-FIP region in the chromosphere and the low- from the high-temperature region in the corona.

In a study of solar wind streams, *Siscoe and Intriligator* [1993] found the proton specific entropy, which is proportional to $\ln(T/n^{\gamma-1})$, and which should be a constant of the flow, to be enhanced in the high-speed stream and further that an abrupt increase is a good indicator of the stream interface at the leading edge. ($T/n^{\gamma-1}$ is referred to as the specific entropy argument, where T is the proton kinetic temperature, n is the proton density and γ is the ratio of specific heats [*Siscoe*, 1983].) In this study, the specific entropy argument is compared with the O^{7+}/O^{6+} freezing-in temperature previously reported by *Geiss et al.* [1995] and Mg $^{10+}/O^{6+}$ ratio. A close anticorrelation is found including a discontinuous change in entropy coincident with the trailing edge of the high-speed stream identified in the SWICS data.

Although it has been shown that the trailing edges of high-speed streams, when mapped back to the Sun, originate within a narrow range of solar longitudes corresponding to the boundary of the coronal hole from which the stream emanates [*Nolte et al.*, 1976], no specific feature has been previously identified as the interface at the trailing edge. We identify this discontinuous change in entropy as a marker of the trailing edge interface. Identification of this interface in SWOOPS data provides a distinct advantage since it is sampled at relatively high time resolution.

2. Analysis

Ulysses plasma and magnetic field data from mid-June 1992 through mid-July 1993 were used for this study. During this time, Ulysses sampled the recurrent solar wind stream more than 15 times. The specific entropy argument, $T/n^{\gamma-1}$ was calculated for the solar wind protons using a value of $\gamma=1.5$. (This value is consistent with the mean solar wind value, $\gamma = 1.46$ derived empirically in a study using Helios 1 data [*Totten and Freeman*, 1995].) The specific entropy then reduces to $T/n^{1/2}$, with T in degrees K and n in cm^{-3} . One hour averages of the entropy argument within the trailing edge were inspected to identify an

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abrupt drop from a high value in the fast wind to a lower value in the slow wind which characterizes the interface. Subsequently higher time resolution data were used to examine the interfaces in detail.

Figures 2a and 2b show various solar wind parameters along with the SWICS composition measurements from 1992 and 1993 respectively. In the top panel of each figure, the alpha particle velocity (V_α , dashed line) measured by SWICS along with the corresponding freezing-in temperature (T_o , solid line) derived from the O^{7+}/O^{6+} ratio are shown. The freezing-in temperatures presented here are those determined by *Geiss et al.* [1995]. Note that T_o is plotted on a logarithmic scale and in an inverse sense to emphasize correlations with the solar wind velocity. Hour averages of the proton entropy, density, temperature, magnetic field strength, and total pressure (thermal plus magnetic) are shown in the subsequent panels. The entropy is clearly enhanced in the high-speed stream (shaded) and a discontinuous jump occurs at both the leading and trailing edges. Although the entropy is generally declining throughout the trailing edge, the interface is characterized by a distinct discontinuous drop. The vertical lines indicate the leading and trailing interfaces as identified by visual inspection of the hour averages. For all but stream 8 an abrupt interface was identified at the trailing edge. Although there is no remarkable change in any individual solar wind parameter that would lead one to identify it as a boundary, the entropy gives a strong signature. Typically, the interface occurs during the declining portion of the speed profile where the solar wind speed is low, and as can be seen from the bottom panels, in the rarefaction region where the pressure is a minimum. Coincident with this jump in entropy but occurring over a longer time period is a change in the oxygen freezing-in temperature, T_o , measured by SWICS. Variations in Mg/O have been shown to be virtually identical to T_o but are not shown here.

Once the interface was identified in the hour averages, higher-resolution data (sampled in intervals of either 4 or 8 min) were examined. In order to calculate the duration of the interface in a systematic manner and subsequently infer its thickness, the start and stop times were first estimated by visual inspection of the data. Next, an hour average of the entropy before and an hour average after the interface was calculated. The actual start and stop times of the interface are the times at which the entropy attains the upstream and downstream background averages respectively. High time resolution data are shown in Figure 3 for several representative examples used in this study. The shaded region shows the duration of the interface. The events identified as trailing edge interfaces are shown in Table 1. The start and stop times of the interfaces and their duration, are tabulated here. The average duration is 51 minutes and the most abrupt interface occurs in only 5 minutes, which implies a boundary thickness of roughly 10^5 km (assuming a corotating time stationary structure). The minimum and maximum speed on either side of the interface and the speed at the interface are also given, where the minimum speed is the lowest value occurring in the trough of the slow solar wind following the interface and the maximum is the highest speed of the crest preceding it.

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F3

T1

3. Superposed Epoch Analysis

To emphasize the characteristic changes across the boundary, a superposed epoch analysis of the specific entropy argument and other relevant solar wind parameters was performed at sixteen interfaces. (For one event there was a data gap, and for another an abrupt interface could not be identified.) Hour averages of the plasma data were used for this analysis and the epoch time corresponds to the abrupt drop in entropy. Error bars indicate estimates of the error of the mean ($\sigma_a/N^{1/2}$), where σ_a is the standard deviation and N is the number of events contributing to the average. Figure 4 shows the results of the superposed epoch analysis for specific entropy and various other solar wind parameters. As can be seen in the top panel, specific entropy decreases roughly by a factor of one third at the interface. This decrease can be accounted for by a jump in density (Figure 4b) as the temperature (Figure 4c) gradually decreases on the trailing edge of the stream. Since hour averages are used, the abruptness of the interface which is apparent in the high resolution data is not accentuated here. A distinct drop in the alpha/proton ratio (Figure 4d) occurs across the boundary from a value of ~5% typical of the fast wind to ~4% more characteristic of the slow solar wind. This well-known change was first reported by Gosling *et al.* [1978] in their study of leading edge interfaces and in fact it is this difference that caused him to suggest that two types of unmixed plasma exist. The total pressure (thermal plus magnetic) shows that there is no significant pressure gradient across the interface. In the bottom panel the $\text{Mg}^{10+}/\text{O}^{6+}$ ratio from the SWICS instrument is plotted. The accumulation time of more than 3 hours ensures errors of less than 20% in the density. For the superposed epoch analysis an average is calculated for each hour interval. Since the resolution of the composition data is more than 3 hours, not all 16 cases will have a data point that falls within a given hour interval thus not all events will contribute to each hourly average. The jump which is as large as that for the total Mg/O (Figure 1) shows that the $\text{Mg}^{10+}/\text{O}^{6+}$ ratio gives a strong signature of the interface. It should be noted that $\text{Mg}^{10+}/\text{O}^{6+}$ does also reflect the freezing-in temperature (which is determined from the ratio of charge states), in addition to the change in elemental composition; however, since it was readily available for the entire interval of this study at the National Space Science Data Center Archive, it was used instead of the total complement of Mg and O. The abrupt changes in Mg/O at the interfaces has already been noted in the aforementioned studies, i.e., Geiss *et al.* [1995] and are consistent with the jump in $\text{Mg}^{10+}/\text{O}^{6+}$.

A superposed epoch analysis was performed on the alpha-proton speed difference, $V_{\alpha p} = |\vec{V}_\alpha - \vec{V}_p|$ and is shown separately for an extended interval in Figure 5. \vec{V}_α and \vec{V}_p are the vector velocities of the alpha particles and the protons, respectively. The results are shown for 48 hours prior to and 16 hours following the trailing interface. In contrast to the superposed epoch analysis of Gosling *et al.*, [1978] which revealed a substantial (~20 km/s) jump at the leading edge, no abrupt change

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occurs across the trailing interface. The decline of $V_{\alpha p}$ with declining solar wind speed along the trailing edge is consistent with the previously documented correlation between V_p and $V_{\alpha p}$ [cf. *Neugebauer et al.*, 1996]. $V_{\alpha p}$ has reached its low interstream value some 10 hours prior to the trailing edge interface. Although the alpha particle fraction changes abruptly at the interfaces, the alpha flow speed relative to the protons does not.

4. Identification and Analysis of Magnetic Field Discontinuities Near the Trailing Interface

Magnetic field data throughout the duration of the interface were searched for major discontinuities. One would expect to identify a tangential discontinuity at the interface separating two plasmas of distinct origins. Typically, discontinuities could be found within the interval defined as the interface, but they were unremarkable in comparison to other discontinuities nearby. These discontinuities were analyzed further in order to classify them as tangential or rotational. To do this, the criteria of *Smith* [1973] as modified by *Neugebauer and Alexander* [1991] were used. In that study a discontinuity was classified as tangential if the ratio of intermediate to minimum eigenvalues determined from minimum variance analysis, $\lambda_2/\lambda_3 > 2$, $\Delta B/|B| < 0.2$, (where ΔB is the change in field magnitude across the discontinuity and $|B|$ is the larger of the fields on either side), $B_n < 1$ nT and $B_n > 2\sigma_n$, where B_n is the normal component of the field across the discontinuity and σ_n is the error in B_n . Half the discontinuities examined could be immediately classified as tangential. Although none of the remaining discontinuities had a large normal component, their classification was inconclusive primarily because the normal component of the field determined from minimum variance analysis was somewhat larger than twice the error, $2\sigma_n$. No further analysis was performed.

5. Discussion

Identification of the eastern trailing edge of a solar wind stream is useful in mapping back features to the solar surface since it suffers less distortion with propagation from the Sun than the leading edge. Because the region is rarefied, the plasma is less affected by acceleration, deceleration and shock formation. Previous studies, in which large-scale velocity structure has been mapped back to the corona, have demonstrated excellent agreement of the mapped velocities in the rarefaction regions with coronal hole boundaries both at 1 AU [*Nolte et al.*, 1976] and as far out as 5 AU [*Mitchell et al.*, 1981]. In this study we have identified a single parameter which is a marker of a well-defined interface within this rarefaction region. Its coincidence with changes in composition, Mg/O , Mg^{10+}/O^{6+} alpha/proton ratio, and oxygen freezing-in temperature indicates it separates two plasma of distinct origins.

Although SWICS composition measurements give a strong indication of the stream interface, the SWOOPS plasma measurements have the distinct advantage of higher time resolution. The SWOOPS plasma instrument has a sampling rate

of 4 or 8 min, whereas the oxygen and carbon freezing-in temperatures require an accumulation of 1 hour's worth of data to achieve satisfactory statistics. In the case of Mg/O ratio, 16 instrument cycles are required, resulting in approximately 3.5 hours time resolution. The intrinsically larger time intervals needed for SWICS (largely a consequence of geometric factor and distance from the Sun) is specific to Ulysses. The CELIAS particle experiment on the SOHO spacecraft can measure ionic and elemental composition with a time resolution of 5 min at 1 AU [Aellig *et al.*, 1998]. Similarly, ACE SWICS has a time resolution of a few minutes. The simple advantage of using the specific entropy argument in identification of the interface is the relative sampling rates of the instruments.

Clearly, dynamic processes affecting the interface at the leading edge, where fast wind is overtaking slow, are quite different from those in the rarefaction region where the trailing interface occurs. Although not considered in detail in this study, Figures 2a and 2b show that the interface at the leading edge of these streams is also marked by an abrupt increase in entropy. The leading-edge interfaces of the streams examined in this study have been investigated in detail by *Wimmer-Schweingruber et al.*, [1997]. In that study the interface was identified first using the typical plasma parameters, density and temperature, and then examined for changes in heavy ion composition, such as the Mg/O ratio and the freezing-in temperatures derived from O^{7+}/O^{6+} and C^{6+}/C^{5+} . They concluded that both differences in charge state and elemental composition give a strong signature of the leading edge interface. Further, they conclude that compositional measurements are essential in determining the locations of more complicated stream interfaces.

The applicability of the polytropic relation, $p/\rho^\alpha = \text{constant}$ has been demonstrated in various analyses of space plasmas. Studies by *Feldman* [1978], *Sittler and Scudder* [1980], *Osherovich* [1993], *Totten and Freeman* [1995], and *Newbury et al.* [1997] are some examples. The typical approach is to determine if the polytropic approximation is valid (by fitting it to the data of interest) and to quantitatively evaluate the polytropic index. As pointed out by *Siscoe* [1983], the quantity which is constant in this expression is related to the specific entropy argument, since the entropy can be expressed as $\ln(T/n^{\gamma-1})$ (with a polytropic index $\alpha = \gamma$ for an adiabatic or isentropic process). Further, it can be shown that this parameter is constant only on a given streamline. In a study using Helios data, *Totten and Freeman* [1995] evaluated the polytropic relation for solar wind protons. The polytropic index, α was found to be independent of speed state and had an average value of 1.46 ± 0.04 . The quantity which should be constant in the polytropic relation p/ρ^α , was evaluated and found to depend on speed state but not on radial distance for the two distances examined, 0.3 AU and 1.0 AU. In another study, *Siscoe and Intrilligator* [1993] compared several large solar wind streams of 1974 at three radially aligned spacecraft (IMP, Pioneers 10 and 11). At the interface itself the entropy was found to increase rapidly, with the values at all three spacecraft essentially identical, again confirming the constancy property of the specific entropy. *Goldstein et al.* [1996] in a study of

Ulysses high latitude solar wind measurements, examined expressions of the functional form $V = AT/(n^s r^t)$, where the power law indices s and t were chosen to obtain the best fit to V . They found that $T/n^{1/2}$, which is simply the specific entropy argument with a choice of $\gamma = 1.5$, was best predicted by the velocity in both Northern and Southern hemispheres. These studies validate the choice of $\gamma = 1.5$ for the solar wind and suggest the notion of specific entropy as a streamline constant is valid.

The thickness of the solar wind stream interface has implications regarding its origin. *Burlaga* [1974] proposed that the interface develops in interplanetary space as a consequence of nonlinear stream evolution, generated by a temperature difference in the corona. The interface *Burlaga* envisioned was roughly 10^6 km thick at the leading edge of the stream. *Gosling* [1978] viewed the structure as a sharper interface which is likely to have formed back at the Sun and not in interplanetary space. In that study the interfaces occurred over a very short duration (shorter than the sampling time of the instrument) corresponding to a structure of the order of 10^4 km in width. The thickness of the interface at the trailing edge as determined in this study is some where between these two extremes. However, the trailing interface is located in the rarefaction region, which is expanding with distance from the Sun and is likely to be thicker than the interface at the leading edge where compressive effects are likely to influence the structure.

It should be noted that the usefulness of entropy in identification of solar wind streams is limited to portions of the solar cycle during which well-defined streams predominate (such as the ascending and descending phases). A cursory scan of Ulysses data from 1990 to 1992, just after the last solar maximum showed that the strong signal in the entropy parameter is clearly diluted when recurrent streams are not present and transient phenomenon predominate.

6. Conclusions

The solar wind proton specific entropy argument has proved useful in identification of the interface at the trailing edge of a recurrent stream observed at 5 AU by the Ulysses spacecraft. For almost every occurrence of this stream at the spacecraft an interface separating high entropy, fast solar wind flow from slower interstream wind could easily be identified. A distinct drop in the alpha/proton ratio occurs across the boundary from values typical of the fast wind to those more characteristic of the slow solar wind. The interface coincides with but is more abrupt than changes observed in the total Mg/O ratio, Mg^{10+}/O^{6+} , and the freezing-in temperature derived from O^{7+}/O^{6+} . We conclude that the solar wind plasma parameters which characterize this interface are well preserved at distances as great as 5 AU.

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Table 1. Trailing Edge Interfaces

Stream	Duration (min)	Start Time			Stop Time		V_{\max}	V_{\min}	V_{int}	Comments
		Year	DOY	hour:min:s	DOY	hour:min:s				
1	32	1992	193	23:13	193	23:18	615	404	485	plasma data gap from 219 0657 - 1753 UT
2	-		219		219		729	423	525	
3	8		245	17:36	245	17:48	788	423	491	
4	8		272	15:42	272	17:21	820	428	477	CME from day 319 0945 to day 320 2250 UT
5	36		298	09:28	298	09:48	771	400	483	
6	24		322	15:17	322	15:41	988	434	568	
7	40		346	23:20	347	00:38	749	377	551	boundary not distinct (not included in superposed epoch analysis)
8	-	1993	- 6-10	-	-	-				
9	32		41	13:59	41	16:07	780	435	464	
10	29		64	02:05	64	02:19	753	398	547	CME, magnetic cloud day 160, 2120 - 164, 0130 UT
11	16		92	18:30	92	18:46	805	427	488	
12	8		121	03:36	121	03:53	805	549	571	
13	56		139	20:32	139	21:27	828	557	671	possible interface
14	63		164	02:18	164	03:15	858	541	684	
15	24		195	15:01	195	15:40	812	546	686	
16	44		227	09:22	227	10:18	788	660	691	possible interface
17	96		242	01:05	242	03:33	864	672	710	
18	167		272	09:07	273	09:55	800	677	712	

The times of trailing edge interfaces for 18 streams identified in Ulysses data in 1992-1993 are tabulated here. The duration is listed, as are the start and stop times. Also noted are the solar wind velocity at the interface and the minimum and maximum velocity on either side of the interface.

Figure Captions

Figure 1. Superposed epoch analysis of T_o , the freezing-in temperature derived from the ratio O^{7+}/O^{6+} , the Mg/O ratio and the solar wind speed represented by the alpha particle speed measured by the Solar Wind Ion Composition Spectrometer from *Geiss et al.* [1995].

Figure 2. Overview plot of data used in this study showing data from (a) 1992 and (b) 1993 respectively. The top panels shows the oxygen freezing-in temperature (solid line) and solar wind velocity (as determined from the alpha velocity measured by the SWICS instrument). Hour averages of the specific entropy argument as defined in the text. Solar wind proton density, kinetic temperature, field magnitude, and total pressure (thermal plus magnetic) are also shown.

Figure 2. (continued)

Figure 3. Stack plot showing proton specific entropy argument at high time resolution at the trailing interface for several of the streams examined in this study. The stream number is noted in the top right corner of each panel. Each tic on the horizontal axis denotes 1 hour. The shaded region shows the duration of the interface.

Figure 4. Results of a superposed epoch analysis for 8 hours either side of the trailing edge interface. The specific entropy, proton density and temperature, alpha:proton ratio, and Mg^{10+}/O^{6+} ratio are shown. The error bars indicate error of the mean ($\sigma_s/N^{1/2}$), where σ_s is the standard deviation and N is the number of events contributing to the average.

Figure 5. Superposed epoch analysis for the alpha proton velocity difference over an extended interval, 48 hours prior to and 16 hours following the trailing interface.

Figure Captions

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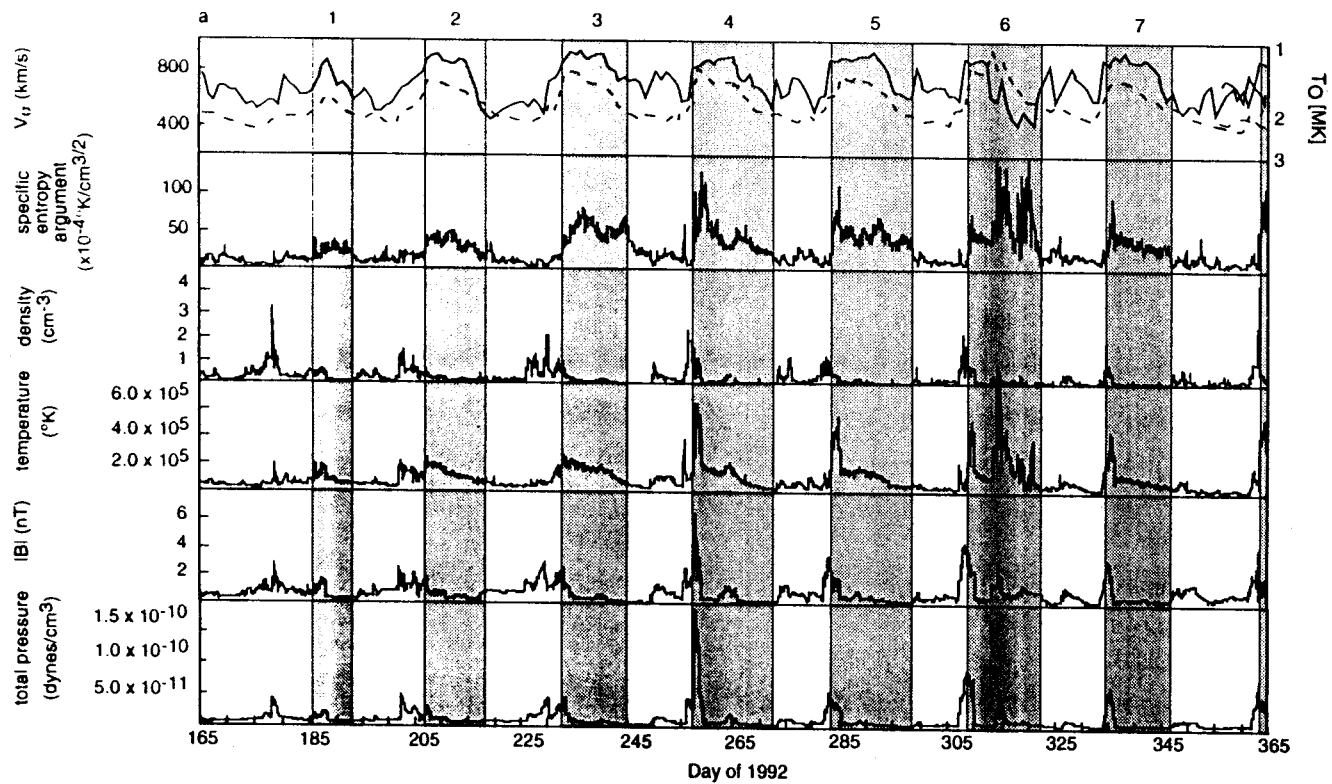
Figure 2. (continued)

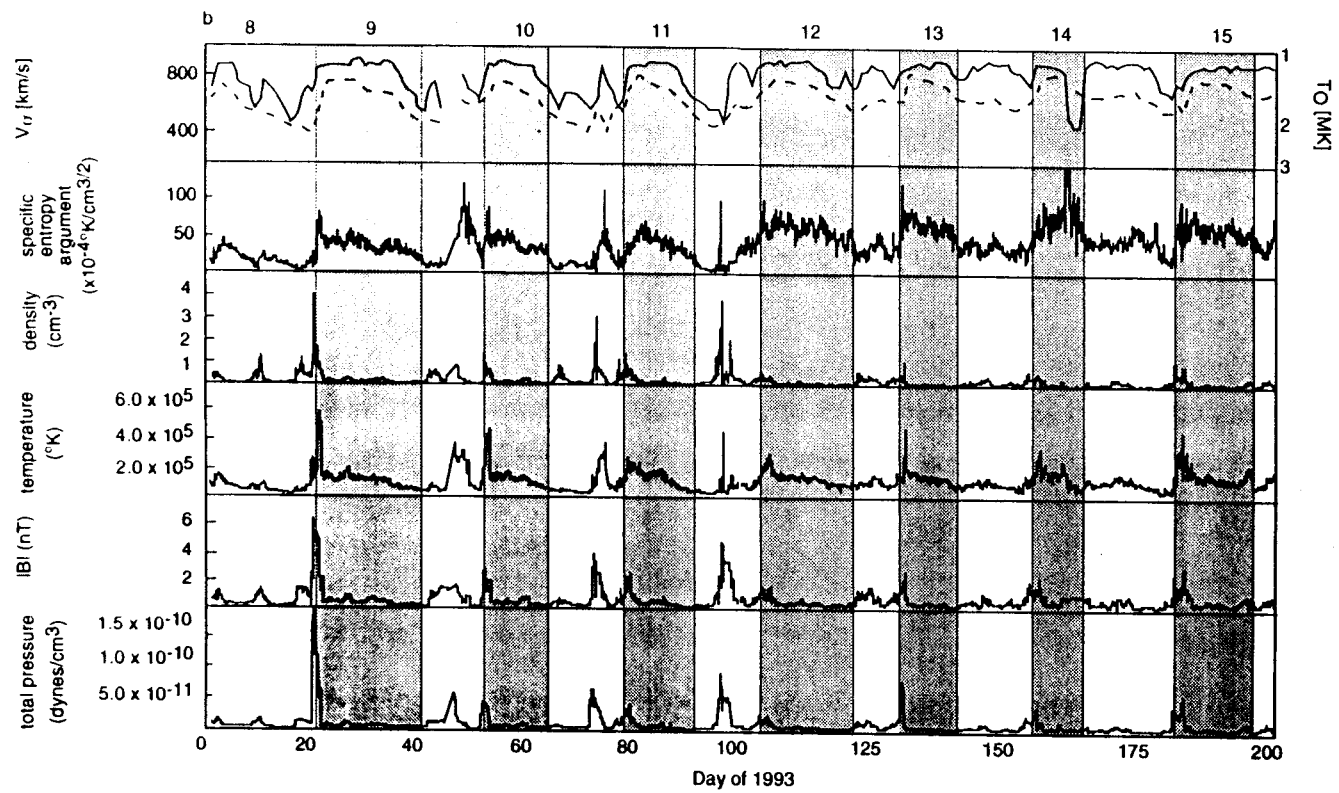
Figure 3. Stack plot showing proton specific entropy argument at high time resolution at the trailing interface for several of the streams examined in this study. The stream number is noted in the top right corner of each panel. Each tic on the horizontal axis denotes 1 hour. The shaded region shows the duration of the interface.

Figure 4. Results of a superposed epoch analysis for 8 hours either side of the trailing edge interface. The specific entropy, proton density and temperature, alpha:proton ratio, and Mg^{10+}/O^{6+} ratio are shown. The error bars indicate error of the mean ($\sigma_s/N^{1/2}$), where σ_s is the standard deviation and N is the number of events contributing to the average.

Figure 5. Superposed epoch analysis for the alpha proton velocity difference over an extended interval, 48 hours prior to and 16 hours following the trailing interface.

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specific entropy
($\times 10^{-4} \text{ } ^\circ\text{K/cm}^{3/2}$)

